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Comparison of Different Polynomial Degrees for Correcting the Instrumental Drift of Scintrex CG-5 Autograv Gravimeter

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Abstract

Reducing the gravity field raw data influenced by drift effect is remarkable as a pre-processing correction step. Most of the research groups deal with the drift effect as a linear function when reducing the drift effect from the gravimeters raw data. This would be suitable for short time period of gravity data. However, for a long time period this will lead to a poor approximation to the time-varying components of the gravity field.
The main objective of this contribution is to correct the drift effect comparing linear in addition to five non-linear polynomial functions using about one month (from 12 December 2019 till 13 January 2020) of gravity data measured by the Scintrex CG-5 Autograv gravimeter.
The results of this investigation show that the non-linear drift functions surpass in the accuracy of the linear drift. In particularity, the non-lineal 6th-degree polynomial provides the most promising drift of sub nanoGal/day accuracy. Reduced gravity signal from the drift effect using the 6th-degree polynomial shows the standard deviation of about 3.310 μGal with respect to the linear drift (29.59 μGal) and the other applied non-linear polynomials (2nd – 5th degree) ranging from 17.35 – 8.44 μGal, respectively.
Since the drift effect may differ from gravimeter to another depending on the sensor age, temperature, and other external influences such as vibration due to transport and shocks, the outcome of this study should be considered for any gravity field survey accomplished by CG-5 gravimeter. Therefore, it is recommended to apply non-linear polynomial functions to correct and interpret the gravity variations in an optimal way.

Keywords: Gravity Field Data. Scientrex CG-5 Auto Gravimeter. Drift Effect. Non-linear polynomial degrees

INTRODUCTION

Gravity accelerations are usual target quantities in physical geodesy, which define the direction and magnitudes of the gravity vector and thus define many aspects such as the plumb line direction, the flow of water, satellite orbits, etc. The SI (System International) unit of gravity is m/s^2, however this paper uses Gal (i.e. cm/s^2, named after Galileo Galilei (1564 – 1642)) as cgs (centimeter gram second) unit for gravity measurements. For regional and local gravity surveys, it is preferable to use smaller values of Gal, namely mGal (i.e. milliGal=10^{-5} m/s^2) and/or μGal (10^{-8} m/s^2). Basically, there are two types of gravity meters (gravimeters); the absolute and relative gravimeters. The absolute gravimeters measure the absolute values and the relative ones measure the differences between gravity readings.

In 1984, the Canadian company Scientrex Ltd. (Concord, Ontario) has started the development of the first fully automated relative gravimeter (Autograv) of types Autograv CG-3 (Hugill, 1984) followed in 1990 by CG-3M (Hugill, 1990; Scintrex, 1995; Seigel et al., 1995) for mineral exploration, oil and gas exploration, and microgravity and geodetic applications. In 2005, a new generation, namely Scintrex CG-5 Autograv (Scintrex, 2012) with a reading resolution of 1 μGal and an extensive measurement range of over 8 Gals has been developed. A new design, Scintrex CG-6 (Scintrex, 2019), is now in the market since 2016, whose reading resolution reaches 0.1 μGal. Unlike CG-3 and CG-5, the CG-6 is supported by a 7-inch tablet computer, which is prepared for field use with Windows 7 and Windows 10 as well the "LYNX LG Land Gravity" software to allow the observer to monitor and control the measurement remotely during the data capture. Figure (1) shows the three developed Scintrex CG-3/3M, CG-5, and CG-6 Autograv gravimeters.

Figure 1. The three developed Scintrex Autograv gravimeters. From left to right: CG3/3M, CG-5, and CG-6.

For accurate interpretation of gravity measurements by any gravity survey, gravity readings have to be reduced and corrected from numerous influences (Torge, 1989). Some of these influences must be pre-processed independent on the target of the gravity survey and others are processed depending on the survey target. In the pre-processing step, the gravity data must be corrected from instrumental height, instrumental drift, tides, and ocean loading, air pressures. In the processing step, the gravity data are corrected from latitude variation, heights (free-air correction), mass change (i.e. simple Bouguer correction), terrain (detailed Bouguer correction), and isostatic and topographic corrections, etc.

The main objective of this study is to investigate the essential effect “the instrumental drift” of the Scintrex CG-5 Autograv gravimeter (#807) (Figure 1, middle) installed in the basement of the Institute of Geodesy and Geoinformation (IGG), the University of Bonn (UB). This will be done by measuring the gravity through a time span of one month and interpolate the gravity signal applying different degrees of polynomial functions to investigate which of these degrees are suitable when reducing the drift effect from the gravity data recorded by the Scintrex CG-5 Autograv device.

In the following, the operational characteristics of the applied device (CG-5 Autograv) are described in Section 2. Correction of drift using various polynomial degrees is presented in Section 3. The results are discussed in Section 4. Finally, some conclusions are given in Section 5.

2. Operational Characteristics of CG-5 Autograv relative gravimeter

The Scintrex CG-5 Autograv installed in the basement of UB-IGG is shown in Figure 2. As indicated in Table 1, it has a measuring range from 0 to 8000 milligals (mGal) and a reading resolution of 1 μGal. It measures a frequency of 6 Hz. The manufacturer specifies the repeatability as 5 μGal. The device can computationally compensate for inclinations of up to 200 arcseconds. The drift is given as less than 20 μGal per day.

In principle, the zero-position elastic spring gravimeter has a proof mass located in the middle of a capacitive transducer using an electrostatic nulling. In the course of measurement, an automatic feedback circuit applies DC voltage to the capacitor plates. The electrostatic force acting on the proof mass brings it back to the null position. The feedback voltage is proportional to relative value of gravity (Scintrex, 2006), which provides the output finally in terms of gravity readings.

Figure 2. The Scintrex CG-5 Autograv of the UB-IGG gravity station installed on a pillar (left) and on a tripod (right).

Table 1. The Scintrex CG-5 Autograv Characteristics as provided by the Scintrex company.

Sensor type	Fused Quarz (Quarzgals)
Resolution	1 μGal
Standard deviation	5 μGal
Range of measuring	8000 mGal
Drift	20 μGal/day
Dimensions [L×W×H]	22cm x 20cm x 30cm
Weight	8 kg

Since the CG-5 is a classic linear spring gravimeter (Scintrex, 2006), the principle of operation of a spring gravimeter based on HOOKE's law (Torge, 1989) reads

$$\frac{\Delta l}{l_0} = \frac{F}{A \cdot E} \quad [1]$$

This describes the relationship of the relative length change of a bar $\Delta l/l_0$ to the force F applied to it and the cross-section of the bar A, multiplied by the material-dependent modulus of elasticity E. Since the tensile force F is made up of weight and mass, it can be written as

$$F = m \cdot g \quad [2]$$

So the gravity acceleration g can thus be achieved by inserting Eq. [2] into Eq. [1] as

$$g = \frac{\Delta l}{l_0} = \frac{A \cdot E}{m} \quad [3]$$

For the spring, a spring's constant (k) resulted from the elasticity module of the used wire, the number of turns and the diameter of the spring. What obtained in Eq. [3] can be simplified to

$$g = \frac{k}{m} \cdot \Delta l \quad [4]$$

The spring's material, built inside the CG-5 from NiFe-Alloys and quartz, has the advantage of a linear thermostatic coefficient with small thermal expansion coefficient. Besides, the measuring system (i.e. the CG-5 spring) is protected against changes in the outside temperature (thermostat), air pressure (pressure-tight housing) and also magnetic independence (Torge, 2003) as long as the magnetic field changes are less than ten times the earth's magnetic field (Scintrex, 2006). This linear structure allows the change in spring's length to be measured directly which is done via the restoring forces. A voltage applied to the capacitor's plates surrounding the mass ensures that the mass returns to its starting position (Scintrex, 2006). The amount of voltage applied is a measure of the change in length of the spring. In order to obtain a more precise measurement, the spring, and the DC circuit are placed in a vacuum chamber, which is also monitored by some sensors (e.g. temperature, tilt).

3. Correction of CG-5 Autograv Drift using linear and non-linear polynomial degrees

3.1. Drift Effect

The CG-5 Autograv as mentioned in the previous section is based on zero-position elastic spring which may be affected by temporal changes due to some reasons. This effect is called gravimeter drift. Possible reasons for a drifting zero-position are addressed by Timmen and Gitlein (2004) and Torge (1989) such as the ageing process of spring material, external temperature changes, and uncompensated changes of atmospheric pressure and elastic hysteresis effects due to vibrations, shocks, and inclinations acting on the measurement system during transport.

As noted by Repanic and Kuhar (2017), an advantage of Scintrex gravimeters is that the gravimeter drift behaves approximately linearly with time. In a most recent study, Onizawa (2019) dealt with the instrumental drift as a linear function regarding the short-term as well as long-term campaign of the considered stations. However, for the long time period of gravity this will lead to a poor approximation to the time-varying components of the gravity field, and hence, one would incorrectly account for the tidal and drift parts of the field. Thus, it can be well interpolated by means of repeated measurements on one specific station, which is the scope of this paper.

3.2. Drift Correction Procedure

Before applying drift correction, the raw gravity date is mainly affected by the Earth tides, which is subject to the attraction of the Sun and the Moon with the other celestial bodies to the Earth's body. This effect reaches about ±300 μGal. Therefore, one must first reduce the tidal effect in order to be able to detect accuracy in terms of tens of μGals when correcting the drift effect.
This influence is modeled in the CG-5 using the so-called Longman formula (Scintrex, 2006), which compensates for the earth tides with a uniform amplification factor for all tides and frequencies (Longman, 1959). The UB-IGG uses empirically computed tide parameters based on the ETERNA3.30 (Wenzel, 1996) software package determined at the Odendorf station in Bonn using

amplification factors for individual frequency for the entire frequency bands of the tide model. The tidal model is used for the evaluation at the corresponding times of the gravity measurements. This works with the tidal catalog presented by Tamura (1987). Figure (3) shows the discrepancies between both tides effect computed by the Scintrex CG-6 (internal) and ETERNA3.30 for the applied time span of one month of gravity observations starting from 12 December 2019 till 13 January 2020.

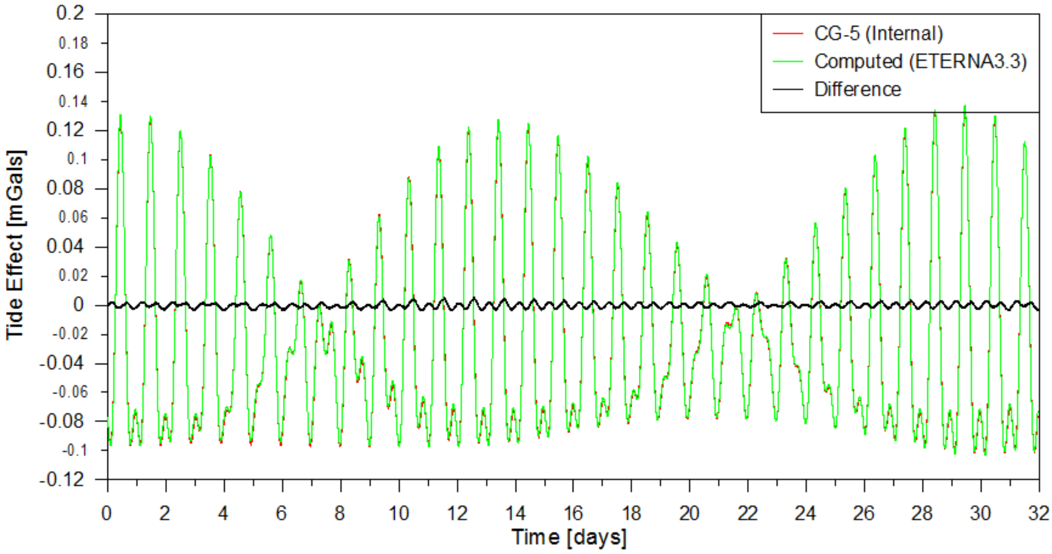

Figure 3. Tides effect in terms of mGal as computed by the Scintrex CG-6 (internal) (red-curve) and ETERNA3.30 software package (green-curve).

As seen, there are differences between the both computed tidal effect, which are due to the tidal loading effects that the ETERNA3.30 take them into consideration. However, the difference is between -3.94 μGal and 5.16 μGal. Therefore, the outcome of ETERNA3.3 tide corrections has been used to correct the gravity observations from the tide effect.

Regarding the drift correction, the manufacturer states that the long-term drift should be checked due to the stress relaxation in the elastic system which leads to uniform change in reading with time. This process is much more pronounced at the beginning of a spring's life cycle. From this check, a drift resulted in as in the following formula (Scintrex, 2006)

$$Drift_{Corr.} = (t - t_S) \cdot Drift \quad [5]$$

Where *Drift* is the drift constant with units of mGal/24 hrs., t_s is the drift correction start time and t is the time at which the samples are taken. The $Drift_{Corr}$ can be determined via a program implemented in the CG-5 gravimeter (Scintrex, 2006). Furthermore, the calculation of the parameter "by hand" is offered using the following formula (Scintrex, 2006)

$$Drift = Drift_{Old} + \frac{R_2 - R_1}{T_2 - T_1} \quad [6]$$

Eq. [6] represents a simple relationship between the old drift parameter $Drift_{Old}$ and the new one *Drift*, which can be obtained by adding a quotient from the differences between two successive gravity readings R_1 and R_2 and their corresponding times T_1 and T_2 to the old drift. As mentioned, this would be useful in short gravity recording, but would lead to inconsistent drift estimation for long-term gravity observations. In the current paper, linear and different non-linear polynomial function at different degrees have been used to estimate the long-term drift (here only 2,…,6). Generally the interpolation polynomial for a degree *n* read:

$$P(x) = a_1 x^n + a_2 x^{n-1} + a_3 x^{n-2} + \cdots + a_n x + a_{n+1} \quad [7]$$

In case of gravity readings with corresponding observation times, the interpolation polynomial of the 6th degree can be written as:

$$\Delta\mathbf{g}(i) = a_1(\mathbf{t}(i))^6 + a_2(\mathbf{t}(i))^5 + a_3(\mathbf{t}(i))^4 + a_4(\mathbf{t}(i))^3 + a_5(\mathbf{t}(i))^2 + a_6\mathbf{t}(i) + a_7 \quad [8]$$

Where **g** and **t** are matrices containing the gravity observations and times. The regression problem is formulated in matrix format as:

$$\Delta\mathbf{g}(i) = \mathbf{t}(i) \cdot \mathbf{a} \quad [9]$$

The vector **a** of Eq.[8] contains the polynomial coefficients to be found. For the 6th polynomial degree, Eq [9] would be written as:

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$$\Delta\mathbf{g}(i) = \left[(\mathbf{t}(i))^6 \; (\mathbf{t}(i))^5 \; (\mathbf{t}(i))^4 \; (\mathbf{t}(i))^3 \; (\mathbf{t}(i))^2 \; (\mathbf{t}(i)) \; \mathbf{1} \right] \cdot \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \\ a_7 \end{bmatrix} \quad [10]$$

4. RESULTS

In the period from 15 December 2019 till 16 January 2020 the gravity data have been recorded on the measuring pillar of the UB-IGG basement with the Scintrex CG-5 Autograv gravimeter CG-5 (#807). Before recording the gravity readings, the CG-5 has been calibrated using the well-known test programs "Sensorcheck" and "Test Cross Coupling". Using the Matlab function polyfit (see The Mathworks, 2019), the polynomial coefficients of Eq. [10] could be estimated. Correspondingly, the function polyval was used to evaluate the polynomial at all points of the gravity readings.

The gravity observations are plotted before and after applying the tide and drift corrections as shown in Figure (4). The raw gravity data (given by the black curve) show a sinusoidal behavior due to the diurnal and semi-diurnal tidal amplitudes. After subtracting the tidal effect, which was computed by ETERNA3.3 software given in Figure (3), from the black curve of Figure (4), the cyan curve has been attained. However, the reduced gravity (after tidal effects) still shows a remaining trend, which is interpreted here as drift signal. Therefore, the drift trend has been estimated using different degrees of a polynomial function and has been then subtracted from the reduced gravity signal (cyan curve) to provide corrected solutions from both tide and drift effects.

To see the final results more closely, Figure (5) shows the different corrected gravity solutions applying the linear drift and the non-linear ones (i.e. 2nd – 6th degree). It is clearly shown that despite the linear drift (given by dashed red curve of Figure (4)) has been subtracted from the corrected gravity signal (the cyan curve of Figure (4)), still corrected gravity signal (red curve of Figure (5)) is affected by remaining un-modeled drift effect providing standard deviation of about 29.59 µGal as indicated in Table 2. In such gravity/micro-gravity survey purposes such as investigation of underground water, this remaining drift would lead to wrong interpretation.

Despite the 2nd – 5th polynomial degrees provide very low drift per day as shown in Figure (4), the corrected gravity signals are still suffering from the rest drift effect. The 6th polynomial degree outperforms all solutions providing corrected gravity signal of the least standard deviation of about 3.3 µGal (see Table 2). Therefore, one should be very careful when subtracting the drift effect in order to interpret the gravity variation in an optimal way.

To sum up, this study is quite important for researchers and surveyors, who perform field gravity observations by considering the nonlinear drift effect. When one performs short term gravity measurements, a linear drift would be simple and easier to be implemented. In case of longer gravity field campaigns, long-term drift should not be always modelled linearly, but other non-linear functions should be concerned and it would be beneficial to model the long-term drift accurately regarding the Scintrex CG-6 gravimeter.

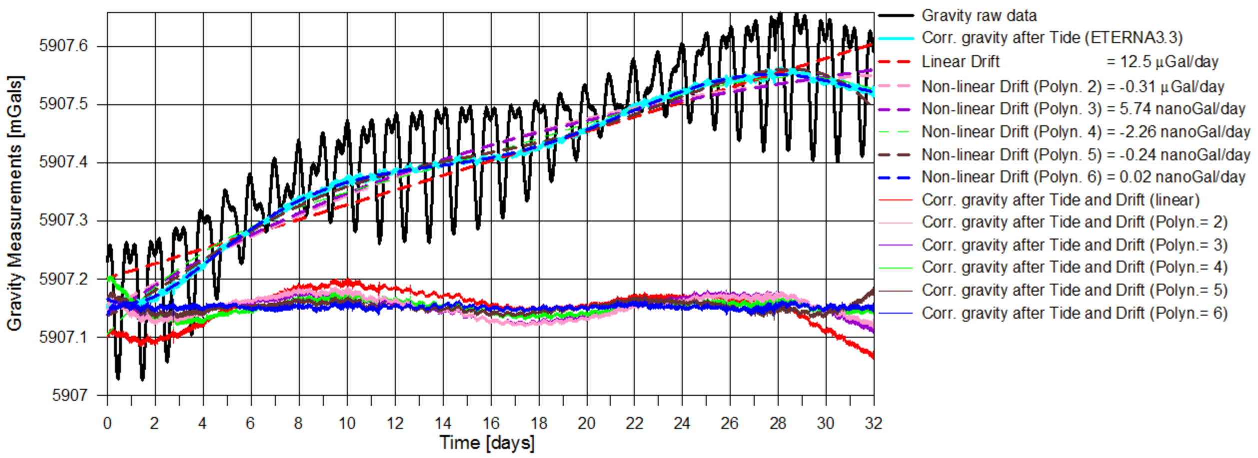

Figure 4. Gravity observations before and after applying drift correction using different polynomial degrees.

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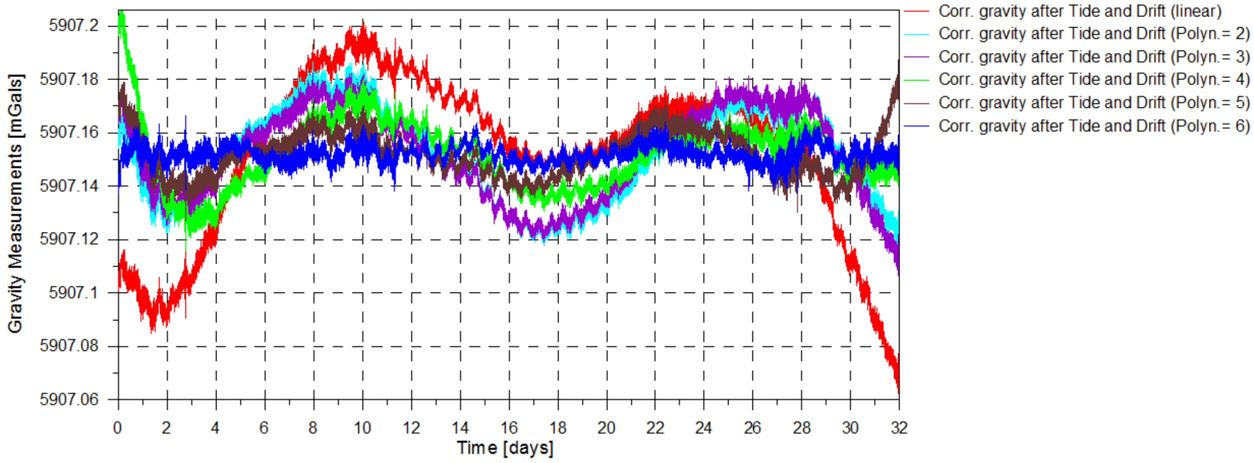

Figure 5. Corrected gravity measurements from tide and drift applying six polynomial degrees.

Table 2. Statistics in terms of standard deviation, mean, minimum, and maximum values given in [µGal] of the corrected gravity signal from both tide and drift effects after applying linear and non linear drift as given in Figure 5

Statistics	Standard deviation	mean	minimum	maximum
Linear Drift	29.59	49.94	-39.75	99.49
Non-linear Drift (Polyn.= 2)	17.35	-0.36	-39.77	30.75
Non-linear Drift (Polyn.= 3)	17.01	-12.80	-58.02	17.64
Non-linear Drift (Polyn.= 4)	12.85	-46.22	-82.34	7.54
Non-linear Drift (Polyn.= 5)	8.447	-14.09	-39.01	21.20
Non-linear Drift (Polyn.= 6)	3.310	13.91	-0.98	28.21

5. CONCLUSIONS

In this paper, different degrees of polynomial function to estimate the long-term drift of gravity data observed by the Scintrex CG-5 Autograv gravimeter for a time period of about one month have been compared. First, the gravity observations have been corrected from the tides effect using both CG-6 internal tide and the ETERNA3.3 software computation. A difference between both tidal corrections between -3.94 µGal and 5.16 µGal has been found. Since the ETERNA3.3 computations consider the oceanic loading parameters, the outcome of ETERNA3.3 tide corrections has been used to correct the gravity observations from tide effect.

Regarding the drift effect, linear in addition to five non-linear (2^{nd} – 6^{th} degree) polynomial functions have been applied. It has been found that in case of estimating drift linearly, the corrected gravity signal is affected by remaining un-modeled drift providing standard deviation of about 29.59 µGal. When applying polynomial degrees 2^{nd} – 5^{th}, very low drift per day has been obtained. However, the corrected gravity signals were suffering from rest drift effect. The 6^{th} polynomial degree had the most promising corrected gravity signal of least standard deviation of about 3.3 µGal. Therefore, it is recommended when modeling the drift effect not to depend only on solving the drift using linear function but other non-linear polynomial functions have to be applied in order to correct and interpret the gravity variations in accurate and optimal way.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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